Tillage and Row Position Effects on Water and Solute Infiltration Characteristics

R. W. Vervoort,* S. M. Dabney, and M. J. M. Römkens

ABSTRACT

Biological channels and wheel track compaction zones increase heterogeneity of soil properties affecting infiltration, runoff, erosion, and solute movement. We hypothesized that crop, tillage system, and position relative to the plant row would alter the rate and pattern of water infiltration into a Grenada silt loam (fine-silty, mixed, active, thermic, Oxyaquic Fraglossudalfs). We compared plant row (ROW), nontrafficked (UTK) and trafficked interrow (TRK) positions for cotton (*Gossypium hirsutum* L.) and grain sorghum [*Sorghum bicolor* (L.) Moench] grown with chisel plow, disk, or no-tillage in the fourth year of a cropping system and tillage study. We used ring and tension infiltration measurements 3 to 10 wk after planting to determine infiltration rate and pore-size distribution. Infiltration patterns and mobile water contents were studied by ponding Brilliant Blue FCF dye [(*N*-ethyl-*N*{4-[(4-{ethyl[(3-sulfophenyl)methyl]-amino}phenyl)(2-sulfophenyl)methylene]-2,5-cyclohexadien-1-ylidene}-3-sulfobenzenemethanaminium hydroxide inner salt, disodium salt)](PYLAM products Co., Garden City, NY) and excavation. Neither tillage nor crop affected ponded infiltration rates that averaged 86.5 mm h^{-1} for the ROW, 18.6 mm h^{-1} for the UTK, and 2.4 mm h^{-1} for the TRK position. Sorghum had more pores (0.04 m^3 m^{-3}) between 1.0 and 0.2 mm diam. than cotton (0.02 m^3 m^{-3}). Deeper and less uniform dye penetration reflected lower mobile water contents under no-tillage (0.04 m^3 m^{-3}) compared to tillage (0.20–0.27 m^3 m^{-3}). This research confirmed the importance of continuous macropores in solute movement, but ponded infiltration rates were only weakly correlated with maximum dye depth and did not reflect tillage system differences in dye patterns.

The effectiveness of no-tillage systems in reducing soil erosion is usually attributed to the energy-absorbing effects of mulch cover and the maintenance of rapid infiltration rates. High infiltration rates for no-tillage systems are typically found in soils with intense earthworm (*Lumbricus terrestris*) activity (Ehlers, 1975; Edwards et al., 1988; Zachmann et al., 1987). On the other hand, compaction caused by wheel traffic on certain areas of fields has locally lowered infiltration rates (Ankeny et al., 1990; Unger, 1996), and increased bulk density (Logsdon et al., 1999).

Preferential flow through biological and structural macropores can have a substantial influence on the depth of water percolation in no-tillage systems where the soil matrix can be largely bypassed (Ehlers, 1975; Thomas and Phillips, 1979; Beven and Germann, 1982; Flury, 1996). In conventional tillage systems, such short circuiting usually occurs only below the disrupted plow layer (Andreini and Steenhuis, 1990; Trojan and Linden, 1994).

Unfortunately, no good agreement exists on the size definition of macropores (Luxmoore et al., 1990). Luxmoore (1981) considered macropores to be all pores draining at 30 mm of H_2O suction. Several researchers have suggested that areas of low bulk density can also function as preferential flow paths even without distinct macropores (Omoti and Wild, 1979; Seyfried and Rao, 1987; Shaw et al., 1997). Lower mobile water contents, defined as the fraction of the wetted soil volume through which solutes are moving (Jury and Roth, 1990), were found under no-tillage systems compared with conventional tillage systems (Singh et al., 1990; van Ommen et al., 1989).

Image analysis has often been used to quantify macropore distribution in soils. Hand drawing on plastic sheets and photographic slides have been the most popular methods for obtaining macropore images, with the first technique reportedly the more successful approach (Edwards et al., 1988; Logsdon et al., 1990; Singh et al., 1990; van Stiphout et al., 1987). At a smaller scale, thin sectioning seems to give good results (Bouma et al., 1977, 1979; Pikul et al., 1988; Shaw et al., 1997). The morphometric data obtained in this manner has been used to calculate saturated conductivities (Bouma et al., 1977, 1979).

Dyes and plaster of Paris have been popular methods for identification of preferential flow paths in field soil (Andreini and Steenhuis, 1990; Ehlers, 1975; Flury et al., 1994; Forrer et al., 1999; Godrathi and Jury, 1990; Omoti and Wild, 1979; Seyfried and Rao, 1987; van Ommen et al., 1989; van Stiphout et al., 1987). Quantification of the dye infiltration patterns in field soil has been more difficult and only two studies have attempted to do so. Van Ommen et al. (1989) used a least squares minimization program called CXTFIT (Parker and van Genuchten, 1984) to fit the convection dispersion equation (CDE) to I patterns. This technique enabled them to calculate the transport active fraction of the soil water. Recently, Forrer et al. (1999) used inverse modelling to analyze two-dimensional dye patterns for longitudinal and lateral dispersion. Their analysis also assumed that the dye flow could be described by a convective–dispersive process. The authors concluded that the high water flow rates resulted in more irregular flow patterns compared with low flow rates.

Our review of the literature suggests that quantification of infiltration patterns is complicated and that no consistent agreement exists on the best techniques to be used for measuring infiltration mechanism differences between tillage and no-tillage systems. The objectives of this study were (i) to characterize the infiltration patterns in no-tillage and conventional tillage systems

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Abbreviations: CDE, convection dispersion equation; K_d, linearized Freundlich adsorption coefficient; *R*, retardation coefficient; ROW, plant row; θ_m, mobile water content; TRK, trafficked interrow; UTK, nontrafficked interrow; z_m, mean travel depth.

Table 1. Soil characteristics for the Grenada silt loam used for the adsorption experiment and retardation coefficient determination.

Horizon	depth	Clay	Silt	pH (H_2O)	pH ($CaCl_2$)	Bulk density
		—— % ——				kg m^{-3}
A	0–0.15 m	16.7	81.3	5.85	5.41	1.42
Bw	0.15–0.46 m	17.6	81.0	4.93	4.23	1.43
Bx	0.46+ m	24.2	74.5	5.46	4.02	1.43

for two crops and three positions relative to the plant row using a combination of infiltration measurements and dye pattern images, and (ii) to quantify the mobile or transport fraction of the soil water content from the dye pattern images.

MATERIALS AND METHODS

The experimental area was located on the Nelson Experiment Farm of the National Sedimentation Laboratory near Como, Tate County, MS. The soils are classified as Grenada silt loam. Three horizons (A, Bw, and Bx) were identified and sampled for further study (Table 1). Bulk samples were air dried and crushed to pass through a 2-mm sieve. Particle-size distribution was determined by pipette and sieving (Kilmer and Alexander, 1949). Soil pH was measured in a 1:2.5 soil/0.01 *M* $CaCl_2$ ratio and 1:1 soil/H_2O suspension using a calomel electrode.

The experimental plots were set up in 1988 using a randomized block design with ten replications. For this study, four treatments in six of the replications were sampled during the summer of 1992. The four treatments sampled were a factorial combination of two tillage systems (no-tillage and conventional tillage) and two crops (cotton or sorghum). The conventional tillage sorghum treatment consisted of a one-pass chisel plow followed by disking and a do-all (rolling chopper and harrow combination) for seedbed preparation. Conventional tillage cotton received an additional row building operation prior to the do-all (Triplett et al., 1996). All conventional tillage plots received sweep cultivation after planting for weed control. All crops were grown continuously, year after year, without rotation. The no-tillage plots were planted flat into killed winter cover crops consisting of hairy vetch (*Vicia villosa* L.) for sorghum and wheat (*Triticum aestivum* L.) for cotton. After 1988, the no-tillage plots received no tillage except that caused by the openers of the planter and cover crop drill seeder.

Individual plots measured 5.5-m wide by 12.1-m long, and comprised six rows. Traffic was controlled using permanent corner boundaries; six-row equipment for planting, spraying, and cultivation; and two-row equipment for fertilization, stalk shredding, cover crop drilling, and harvest. Traffic was not controlled for primary and secondary conventional tillage operations.

During 1992, primary tillage was performed in late April. Cotton was planted on 12 May and conventional tillage plots were cultivated on 10 June, 29 June, and 14 July. Sorghum was planted on 14 May and was cultivated on 15 June and 29 June. Infiltration measurements were made between 2 June and 27 July 1992. For conventional tillage treatments, the time from last tillage to infiltration measurement varied from 6 to 21 d for cotton and from 1 to 22 d for sorghum. In contrast, the time between infiltration and the last tillage operation in the no-tillage plots was 4 yr.

Within each plot three different positions relative to the plant row were identified ROW, UTK, and TRK. Infiltration measurements using a single 254-mm diam. ring infiltrometer (Bouwer, 1986) were made in all three positions. All residue was removed, plants were cut off at the soil level, and the ring was pressed ~50 mm into the soil. Ponded infiltration rates were calculated from the slope of the cumulative infiltration curve. After ponded infiltration measurements, tension infiltration measurements were made using a disc permeameter (Green et al., 1986) at −30-, −60-, and −150-mm H_2O potentials within the ring in the ROW position. A thin layer of fine sand was used to ensure a good contact between the soil surface and the disc permeameter. Tensions used corresponded with minimum pore diameters (d_p) of 1, 0.5, and 0.2 mm by means of Poiseuille's law. Volumes of the different pore classes ($d_p > 1$ mm, 1 mm $< d_p <$ 0.5 mm, and 0.5 mm $< d_p <$ 0.2 mm) can be calculated from the difference between two defining infiltration measurements (Watson and Luxmoore, 1986). After taking infiltration measurements for ~1 h, 2.7 L of 4 g L^{-1} Brilliant Blue FCF dye was ponded in the ring and allowed to infiltrate. Brilliant Blue FCF is an anionic food dye with good visibility, nontoxicity, reasonable mobility in soil, and known chemical characteristics (Flury and Flühler, 1995).

Dye Retardation Coefficient Determination

Adsorption experiments were performed on materials of three soil horizons to obtain independent estimates of the retardation coefficient (R) of the Brilliant Blue FCF dye. Five grams of soil of each horizon was shaken, in duplicate, for 2 h with 20 mL of 0.01 *M* $CaCl_2$ containing eight different Brilliant Blue FCF concentrations (0, 1, 2, 4, 5, 6, 8, and 10 g L^{-1}). Two hours shaking time was assumed to be reasonable, based on the perceived contact time in the soil during the field experiment, but might have been short in light of recent research (Perillo et al., 1998; Ketelsen and Meyer-Winkel, 1999; Germán-Heins and Flury, 2000). Samples were centrifuged and concentrations in the supernatant were determined with a spectrophotometer. A calibration curve was used to convert the absorbence data to concentrations. The equilibrium concentration was plotted against the adsorbed concentration, and a linearized Freundlich model was fitted to the data to determine the adsorption constant (K_d). A linear model is needed to be able to calculate R using the relationship:

$$R = 1 + \frac{\rho_b K_d}{\theta} \qquad [1]$$

in which ρ_b is the bulk density, and θ is the saturated water content assuming this equals porosity calculated from the average bulk density of each horizon (Table 1). Bulk densities were estimated from measurements made in 0.05-m increments in July 1989 for the TRKs and UTKs in the cotton tillage and no-tillage treatments. Measurements were made with a MS-24 CPN[1] (Campbell Pacific Nuclear International, Martinez, CA) that used gamma transmission between a source and a detector separated by 0.3 m to measure wet density. These data were combined with gravimetric soil water samples taken from the two holes made for probe access.

Dye Pattern Characterization

Twenty nine of the 72 possible locations were excavated between 10 to 30 d after the dye was infiltrated (time did not permit excavation of all the locations). The locations consisted

[1] Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the USDA.

of three replications of each of the cotton treatments, except for the conventional tilled trafficked cotton treatment that had only two replications, and two replications of each of the sorghum treatments. Excavation was performed in 25.4-mm depth increments. At each increment, the soil was scraped level, small particles were brushed off with a paintbrush, and two kinds of images of the exposed surface were recorded. A 35-mm camera with a flash mounted upside down on a tripod was used for taking slides. The tripod was lowered into the excavated pit and the same focal distance was used for each shot. The second method used an S-VHS video camera to create 10-s images of each surface. To maintain uniform light quality, the video camera was mounted through a hole in a wooden box that shaded direct sunlight from the surface. Two circular tube lights were mounted around the lens on the inside of the box to illuminate the surface.

Both slides and the video images were transformed to binary pictures, by choosing a visually optimal threshold. The resulting binary images were analyzed for the dyed fraction of the surface area. Both these operations were performed using the CUE-2 (Olympus CUE-2, Olympus Corp., Atlanta, GA) digital image analysis program.

To quantify the dye patterns, the dyed fraction of the area has to be converted to a concentration. Although recently techniques have been developed to calculate dye concentrations from dye patterns (Aeby et al., 1997; Ewing and Horton, 1999), these techniques were not available at the time of this research. In this experiment, we assumed that the dyed area at each depth was uniformly distributed, i.e., each dyed pixel had the same concentration. To take into account the greater adsorption in the lower horizons of the profile, the dyed areas in each horizon were weighed using the K_d value at depth z, $K_d(z)$, relative to the K_d value of the Ap horizon, $K_d(Ap)$. These weighted dyed areas were then assumed to be equal to the resident concentration, $C^r(z, I)$:

$$C^r(z, I) = \text{Dyed Area}(z, I)\frac{K_d(z)}{K_d(Ap)} \quad [2]$$

In which the *DyedArea* (z, I) is the fraction of the area which is stained at depth z, after infiltration I. Assuming the dye was added at the surface as a narrow solute pulse, the mean travel depth can then be calculated using the first moment of the probability density function (pdf), $f^r(z, I)$ of the resident concentrations:

$$z_m = \int_0^\infty z\, f^r(z, I)\mathrm{d}z \quad [3]$$

(Jury and Roth 1990). The resident pdf, $f^r(z, I)$, can in this case be interpreted as giving the distributions of depths, z, the dye might reach by the end of a fixed cumulative infiltration, I (Jury and Roth, 1990). The resident pdf can be defined as:

$$f^r(z, I) = \frac{C^r(z, I)}{\sum_0^{z_{max}} C^r(z, I)} \quad [4]$$

in which $C^r(z, I)$ is the resident concentration calculated using Eq. [2] and z_{max} is the observed maximum depth of dye flow. To calculate the fraction of the profile contributing to the solute transport (the transport volume or mobile water content, θ_m), we can assume that the same mean travel depth could occur from piston flow. In that case:

$$z_m = \frac{I}{R\theta_m} \quad [5]$$

in which I is the total infiltration (m) and R is the dye retardation coefficient relative to water. A weighted R value was calculated for each profile based on the adsorption experiment described earlier, the maximum depth of dye flow, z_{max}, and the thickness of each of the soil horizons (Table 1). The mobile water content calculated with this method is interpreted as a profile averaged transport volume.

A different approach was proposed by van Ommen et al. (1989). Assuming an average pore water velocity, v, which is the water flux, J_w, divided by the volumetric water content, θ, the resident concentration profile calculated using Eq. [1] could be described by the CDE:

$$R\frac{\partial C}{\partial t} = D\frac{\partial C}{\partial z} - v\frac{\partial C}{\partial z} \quad [6]$$

in which C is the observed concentration, R is the retardation coefficient, z is depth, t is the time and D is the dispersion coefficient. The program CXTFIT (Parker and van Genuchten, 1984), which uses a nonlinear least squares fit method, was used to compute the appropriate analytical solutions of the CDE to the dye resident concentration data. The single region model for resident concentrations (Mode 1 in CXTFIT) was used in fitting the relative pore water velocity (v/J_w) and the relative dispersion coefficient (D/J_w). The inverse of the relative pore water velocity can, in this case, be interpreted as the average mobile water content for the profile (van Ommen et al., 1989).

Both approaches have limitations due to the mentioned assumptions. We acknowledge the fact that these assumptions were not always met in this research, but we tried to test the utility of these two approaches to quantify the observed dye patterns.

Statistical Analysis

All statistical analyses were performed using the SAS program (Littell et al., 1991). The data for ponded infiltration, maximum depth of dye penetration, mobile water content, and bulk density were analyzed as a split–split plot design using PROC GLM and calculating LSMEANS (Littell et al., 1991) or with PROC MIXED (SAS, 1996) for ANOVA. Ponded infiltration rates were assumed to be log-normally distributed and transformed before analysis. The tension infiltration data were analyzed as a split-plot design using PROC GLM and calculating LSMEANS. Regressions and K_d coefficients were determined using PROC REG (Freund and Littell, 1991). Statistical differences were tested at the 5% level unless reported differently.

RESULTS AND DISCUSSION

The actual soil characteristics varied somewhat with depth. Table 1 represents the values used for the determination of the retardation coefficient. Analysis of variance indicated bulk density in 1989 had not been influenced by tillage treatments, but significant differences existed ($P < 0.05$) between the TRK and UTK interrows as well as with depth ($P < 0.01$) (Fig. 1). Trafficked interrow areas had greater bulk density than UTK, and the interaction of wheel traffic and depth was also significant. A maximum bulk density occurred at about 0.1-m depth in both the TRK and UTK interrows.

There were no differences between tillage and crop treatments in the 1992 ponded infiltration rates, but significant differences between the row positions were found (Table 2). Infiltration rates in the ROW position

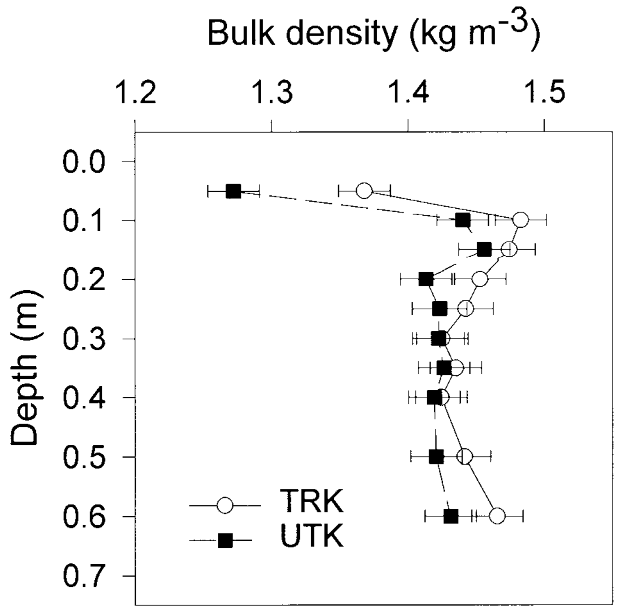

Fig. 1. Bulk density, averaged over replications and tillage treatments, as a function of depth in a Grenada silt loam for the trafficked (TRK) and nontrafficked (UTK) interrows. Error bars indicate ± LSD(0.05)/2. Note the maximum in bulk density at about 0.1-m depth.

were greatest while those in the TRK position were least, probably due to compaction (Ankeny et al., 1990; Unger, 1996). The greater infiltration rate in the ROW position is probably because of denser root growth and more biological activity in that position compared to the UTK and TRK positions. The tillage × row position and crop × row position interaction terms were not significant (data not shown). Although not significant, the highest infiltration rates occurred under no-tillage sorghum followed by tilled cotton, tilled sorghum and no-tillage cotton. This is consistent with earlier research which indicated the lowest runoff from a no-tillage vetch and sorghum treatment among eight treatments studied at the site (Meyer et al., 1999).

Plant row tension infiltrometer measurements indicated a significant difference in infiltration rates at the −30- and −150-mm H_2O potential levels between the cotton and sorghum plots (Table 3). When pore volumes

Table 2. Summary of the ponded infiltration measurements.

Treatment	*n*	Mean ponded infiltration rate
	all rows	mm h^{-1}
	Tillage†	
Tillage	36	17.6a‡
No-tillage	36	13.9a
	Crop§	
Cotton	36	16.7a
Sorghum	36	14.7a
	Row position¶	
ROW	24	86.5a
UTK	24	18.6b
TRK	24	2.38c

† Averaged over rep, crop, and row.
‡ Different letters indicate significant differences at the 0.05 level.
§ Averaged over rep, tillage, and row.
¶ Averaged over rep, tillage and crop.

Table 3. Summary of the infiltration measurements with 20-mm ponded depth and different water potentials (−30, −60, and −150 mm H_2O) measured in the plant rows of the treatments. Total number of measurements was 24 at each tension.

		Mean infiltration rate			
Treatment	*n*	ponded	−30 mm	−60 mm	−150 mm
		Tillage†			
Tillage	12	97.3a‡	23.8a	15.6a	5.5c
No-tillage	12	77.1a	28.4a	16.2a	3.8d
		Crop§			
Cotton	12	80.7a	20.1c	12.8a	5.8a
Sorghum	12	92.8a	32.0d	18.9a	3.4b

† Averaged over rep and crop.
‡ Different letters indicate significant differences at the 0.10 level.
§ Averaged over rep and tillage.

in the different pore classes were calculated by means of the technique described by Watson and Luxmoore (1986), sorghum had a larger volume of pores (0.04 mm^3 mm^{-3}) between 1.0- and 0.2-mm diam. than cotton (0.02 mm^3 mm^{-3}) while the volume of large pores, >1.0-mm diam., was not different between the two crops. Cotton had more pores smaller than 0.2-mm diam. than sorghum, assuming that total porosity was the same between the two crops. The fibrous root system of sorghum thus appeared to create more intermediate pores than the taproot system of cotton. However, the root systems of the winter cover crops in the no-tillage cropping systems were opposite to those of the primary crops, taproot for hairy vetch (after sorghum) and fibrous root for wheat (after cotton). This might have influenced the lack of difference in pores >1.0-mm diam. between the two cropping systems.

When comparing infiltration measurements on a moldboard plowed and no-tillage soil, Sauer et al. (1990) indicated differences in the microscopic capillary length, or mean pore size, with the no-till soil having a larger mean pore size. In our case, there was only a slight statistical difference ($P < 0.1$) in mean pore size at the lowest tension, indicating a difference in mean pore size for the smallest pores, with sorghum and no-tillage having a larger mean pore size than cotton and tillage, respectively.

Dyed soil fraction decreased with depth, which was expected given the finite solute pulse applied at the surface. Preferential or bypass flow was observed on all treatments, though differences in patterns were evident. Some dye patterns clearly showed preferential flow through biological channels (e.g., worm holes, decayed roots) (Fig. 2a). Other patterns indicated preferential flow through part of the domain, without following clear channels (Fig. 2b). The latter areas were probably lower in bulk density (Omoti and Wild, 1979; Shaw et al., 1997).

Deeper flow was observed under the no-tillage treatments as compared with the tillage treatments (Fig. 3a). A sharp drop in dyed area was observed at 0.1-m depth under the tilled cropping systems (Fig. 3a). The tillage operations during the growing season consisted of sweep cultivation of which the maximum depth was about 0.07 m. The sharp drop in dyed area is attributed to a discontinuity in the soil structure created by this tillage

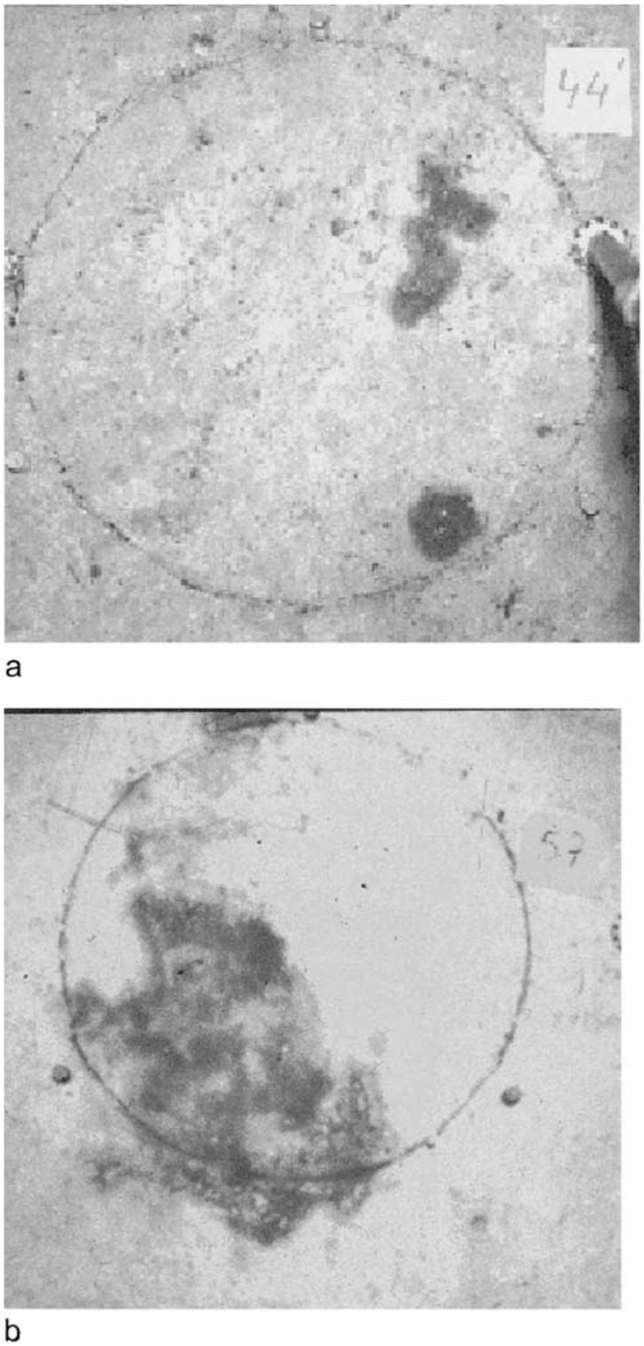

Fig. 2. Example blue dye patterns. (a) Example of preferential macropores flow, 300-mm depth, 4.1% dyed area. (b) Example of preferential area flow, 152-mm depth, 21.5% dyed area. Circle drawn is the original position of the infiltration ring.

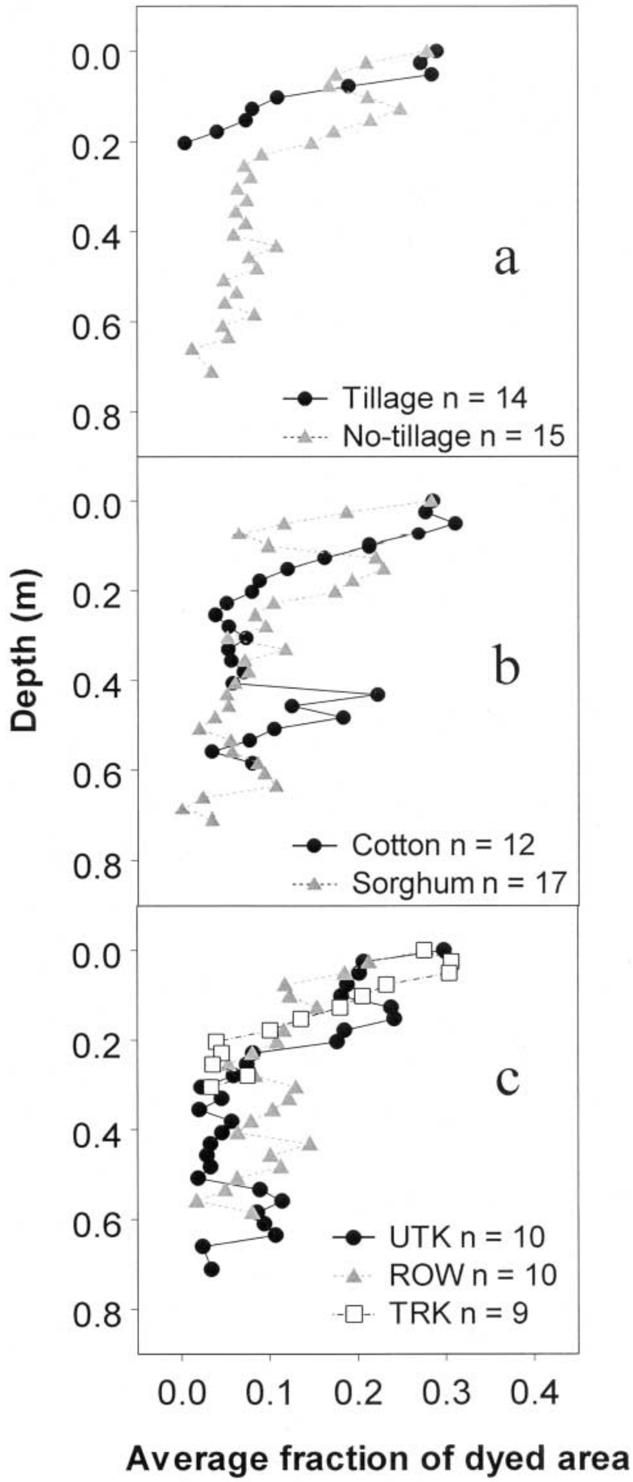

Fig. 3. Average fraction of blue dyed area for the treatments: (a) tillage, (b) crop, (c) row position.

operation (Andreini and Steenhuis, 1990). There were no differences in the maximum depth of dye flow under the different crops, though the average dyed fractions indicate some differences in the pattern of flow (Fig. 3b). Because of the large standard deviations of the observations, no real significance can be attributed to these differences. The dye infiltration in the TRK position indicated a restriction in flow probably because of the compaction observed with the ponded infiltration (Fig. 3c) and bulk density measurements (Fig. 1).

Maximum depth of dye penetration was less for the TRK position than for the other two positions (Table 4); this was consistent with the lower quantity of ponded infiltration. The subset of ponded infiltration data from locations where dye patterns were assessed (n = 29) showed the same statistical differences between treatments as the full data set (n = 72). Thus the dye pattern subset was similar to the full data set.

Maximum depth of dye penetration was positively

Table 4. Maximum depth of dye flow observed after ponded infiltration of 2.3 L of Brilliant Blue FCF dye into areas uniformly cropped or tilled for five years. The total number of measurements was 29.

Treatment	n	average maximum depth of dye flow
		mm
	Tillage†	
Tillage	14	131.3a‡
No-tillage	15	364.8b
	Crop§	
Cotton	17	241.3a
Sorghum	12	254.8a
	Row position¶	
ROW	10	323.4a
UTK	10	271.7a
TRK	9	149.0b

† Averaged over rep and crop.
‡ Different letters indicate significant differences at the 0.05 level.
§ Averaged over rep and tillage.
¶ Averaged over rep, tillage and crop.

correlated with ponded infiltration when the data sets for the tillage and no-tillage were analyzed separately (Fig. 4), but not when analyzed as a single combined data set. The dye consistently infiltrated deeper into the no-tillage soil profiles than the tilled profiles (Table 4). This is consistent with the bypass flow observations for no-tillage systems that has been observed by other researchers (Zachmann et al., 1987; Andreini and Steenhuis, 1990; Trojan and Linden, 1994; Wu et al., 1995). Ponded infiltration rate and maximum depth of dye penetration were better correlated for the tilled treatments ($r^2 = 0.47$, $P < 0.01$) than for the no-tillage treatments ($r^2 = 0.33$, $P < 0.01$) (Fig. 4).

The adsorption experiments indicated that Brilliant Blue FCF dye adsorption increased with soil depth (Fig. 5). Nonlinearity was observed in some of the adsorption experiments, in particular in the Bx and Bw horizon. The adsorption of Brilliant Blue FCF has earlier been found to be strongly nonlinear (Germán-Heins and Flury, 2000). However, in this study the isotherms were fitted with a linear adsorption curve to be able to calculate R . The K_d values, ranging from 2.0 L kg^{-1} for the Ap to 4.7 L kg^{-1} for the Bw horizon, were within the range reported by Germán-Heins and Flury (2000) for several soils. The R values calculated from these K_d values were 7.0 for the A, 15.3 for the Bw, and 13.7 for the Bx horizon. While the R value for the A horizon material was similar to that reported for the same dye in a fine sandy loam soil by Andreini and Steenhuis (1990), the R values in the Bw and Bx horizons were considerably larger. The 1.2 relative retardation of Brilliant Blue FCF dye compared to I reported for a loamy sand field experiment by Flury and Flühler (1995) is also much lower than observed in our subsoil. The differences between earlier reported R values and the values in this research were probably because of differences between the soils. Our subsoil contained 20 to 30% clay, as well as an appreciable amount of amorphous Fe, Al, and Si (Rhoton et al., 1998). Furthermore, the soils studied by both Andreini and Steenhuis (1990), and Flury and Flühler (1995) were calcareous with pH ranging from 6.7 to 8.6. Because Brilliant Blue FCF is a weak acid (pKa = 5.83 and 6.58) it would have been anionic in their studies. In contrast, at the pH of our B horizon material (4.93 and 5.46), dye molecules would have been neutral, and adsorption would increase (German-Heins and Flury, 2000).

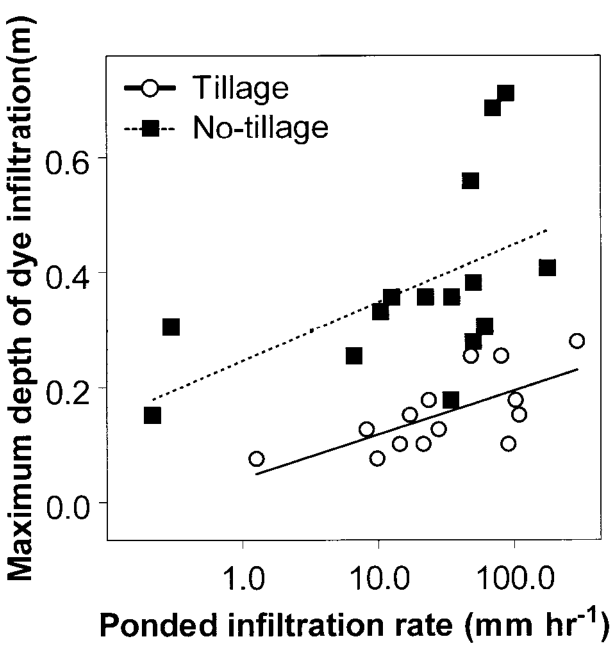

Fig. 4. Relationship between ponded infiltration rate and maximum depth of dye flow, indicating a stronger relationship for the tillage than for the no-tillage treatment.

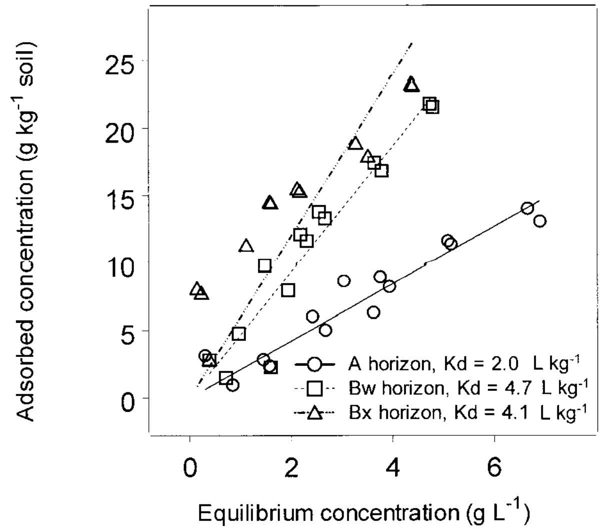

Fig. 5. Adsorption curves for Brilliant Blue FCF dye on the A, Bw and Bx horizons fitted with a linearized Freundlich isotherm. Retardation factors were calculated from the linearized Freundlich adsorption coefficients, K_d values.

Preferential flow under the no-tillage treatment was also indicated by the differences in average mobile water contents calculated from the mean travel depth (Table 5). The tillage treatment had a larger transport volume (more homogeneous flow) than the no-tillage treatment. This would be consistent with the fact that ponded infiltration rates were better correlated with the maximum

Table 5. Mobile water contents calculated using mean dye travel depth (z_m) and CXTFIT.

	z_m		CXTFIT	
Treatment	n	Mobile water content	n	Mobile water content
		$m^3\ m^{-3}$	averaged over reps	$m^3\ m^{-3}$
		Tillage		
Tillage	14	0.20a†	6	0.27a
No-tillage	15	0.04b	6	0.04b
		Crop		
Cotton	17	0.14a	6	0.10a
Sorghum	12	0.12a	6	0.21a
		Row position		
ROW	10	0.12a	4	0.15a
UTK	10	0.10a	4	0.11a
TRK	9	0.16a	4	0.21a

† Different letters (a,b) indicate significant differences within a treatment factor at the 0.05 level.

depth of dye flow under the tillage treatment (Fig. 4). The CXTFIT results indicated the same trend, although the absolute values were different. Neither method found significant differences in mobile water content due to crop or row position.

The difference in the number of observations in the two θ_m estimation methods, reflects the difficulties encountered in using the CXTFIT program. In order to get a solution, the data had to be averaged over the replications. Some of the observed patterns were still difficult to fit and solutions could in some instances only be found using extremely large dispersion coefficients. The fact that the CDE could not effectively fit the observations reflects the fact that the assumptions of an average velocity and homogeneous flow for these soils are not realistic model representations. Preferential flow is characterized by a more than average velocity in part of the flow domain. The fitted relative dispersion coefficients for the no-tillage treatment were greater (mean 5.044 m) than for the tilled treatment (mean 0.221 m), and the r^2 for the fit was worse (mean 0.27 for no-tillage versus mean 0.55 for tillage). This in itself could be an indication of preferential flow under the no-tillage treatment.

Although the dye pattern quantifications attempted here were both rather simple and based on many assumptions, they correctly represented visually observed differences. The mobile water content parameter, θ_m, reflected maximum dye depth, average dyed fraction, and dyed fraction variance. The low calculated mobile water contents indicated that only a small fraction of the profile was used for transport under all treatments (Table 5). In many cases, small θ_m coincided with deep flow, but because of the differences in dye recovery and averaging over replications, we cannot make a strong demonstration of this relationship.

SUMMARY AND CONCLUSIONS

Different infiltration mechanisms appeared to determine the infiltration process under tillage and no-tillage management. While infiltration on tilled areas was relatively uniform, infiltration under no-tillage was nonuniform and controlled by the existence of a continuous pore system. In terms of environmental quality, the implication is that with ponded infiltration, recently surface-applied agrochemicals from no-tilled areas can be more rapidly transported deeper into the soil than from tilled areas. But the distribution of the chemicals already within the soil will also be less uniform under no-tillage, and chemicals residing in the soil might be bypassed by infiltrating water.

The root system of the crop appears to have an influence on the characteristics of the pore system in both tilled and no-tilled areas. Tension infiltrometer measurements indicated more medium sized pores under the sorghum fibrous root system than under the cotton taproot system. In this research, bypass flow seemed to occur mainly through large continuous pores, indicating the importance of these macropores on solute transport to lower horizons. We think it is likely that plant roots also preferentially exploit these macropores in their growth so that root proliferation is most dense in the same limited soil volume where solutes are concentrated.

Blue dye patterns indicated considerable bypass flow under the no-tillage treatment. The average maximum depth of dye penetration was deeper for the no-tillage than the tilled systems. Mobile water contents, indicating preferential flow, were lower for no-tillage than for tillage. Using CXTFIT to fit the CDE to the dye profiles was not very successful, mainly because the observed preferential flow violated the assumptions of the CDE. A different estimation method using a simple piston flow assumption gave similar results with less calculation effort.

Bulk density and ponded infiltration measurements in this study indicated compaction under the TRK position. Plant rows exhibited faster ponded infiltration rates because of more biological activity and flow along plant roots or old root channels. However, ponded infiltration rates measured using single ring infiltrometer did not effectively predict the differences in dye transport under conventional and no-tillage treatments. Combining ponded infiltration rates with measurements at different tensions improved the prediction, but the measurement of infiltration rates using tension and ring infiltrometers still had limited utility in predicting solute transport.

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REFERENCES

Aeby, P., J. Forrer, C. Steinmeier, and H. Flühler. 1997. Image analysis for determination of dye tracer concentrations in sand columns. Soil Sci. Soc. Am. J. 61:33–35.

Ankeny, M.D., T.C. Kaspar, and R. Horton. 1990. Characterization of tillage and traffic effects on unconfined infiltration measurements. Soil Sci. Soc. Am. J. 54:837–840.

Andreini, M.S., and T.S. Steenhuis. 1990. Preferential paths of flow under conventional and conservation tillage. Geoderma 46:85–102.

Beven, K., and P. Germann. 1982. Macropores and water flow in soils. Water Resour. Res. 18:1311–1325.

Bouma, J., A. Jongerius, O. Boersma, A. Jager, and D. Schoonderbeek. 1977. The function of different types of macropores during saturated flow through four swelling soil horizons. Soil Sci. Soc. Am. J. 41:945–950.

Bouma, J., A. Jongerius, and D. Schoonderbeek. 1979. Calculation of saturated hydraulic conductivity of some pedal clay soils using micromorphometric data. Soil Sci. Soc. Am. J. 43:261–264.

Bouwer, H. 1986. Intake rate: Cylinder infiltrometer. p. 825–844. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. ASA and SSSA, Madison WI.

Edwards, W.M., L.D. Norton, and C.E. Redmond. 1988. Characterizing macropores that affect infiltration into nontilled soil. Soil Sci. Soc. Am. J. 52:483–487.

Ehlers, W. 1975. Observations on earthworm channels and infiltration on tilled and untilled loess soil. Soil Sci. 119:242–249.

Ewing, R.P., and R. Horton. 1999. Discriminating dyes in soil with color image analysis. Soil Sci. Soc. Am. J. 63:18–24.

Flury, M. 1996. Experimental evidence of transport of pesticides through field soils—A review. J. Environ. Qual. 25:25–45.

Flury, M., and H. Flühler. 1995. Tracer characteristics of brilliant blue FCF. Soil Sci. Soc. Am. J. 59:22–27.

Flury, M., H. Flühler, W.A. Jury, and J. Leuenberger. 1994. Susceptibility of soils to preferential flow of water: A field study. Water Resour. Res. 30:1945–1954.

Forrer, I., R. Kasteel, M. Flury, and H. Flühler. 1999. Longitudinal and lateral dispersion in an unsaturated field soil. Water Resour. Res. 35:3049–3060.

Freund, R.J., and R.C. Littell. 1991. SAS system for regression. 2nd ed. SAS Inst., Cary, NC.

Germán-Heins, J., and M. Flury. 2000. Sorption of brilliant blue FCF in soils as affected by pH and ionic strength. Geoderma 97:87–101.

Ghodrati, M., and W.A. Jury. 1990. A field study using dyes to characterize preferential flow of water. Soil Sci. Soc. Am. J. 54:1558–1563.

Green, R.E., L.R. Ahuja, and S.K. Chong. 1986. Hydraulic conductivity, diffusivity, and sorptivity of unsaturated soils: Field methods. p. 771–798. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Jury, W.A., and K. Roth. 1990. Transfer functions and solute movement through soil, theory and applications. Birkhauser Verlag, Basel, Switzerland.

Ketelsen, H., and S. Meyer-Winkel. 1999. Adsorption of brilliant blue FCF by soils. Geoderma 90:131–145.

Kilmer, V.J., and L.T. Alexander. 1949. Methods of making mechanical analysis of soils. Soil Sci. 68:15–24.

Littell, R.C., R.J. Freund, and P.C. Spector. 1991. SAS system for linear models. 3rd ed. SAS Inst., Cary, NC.

Logsdon, S.D., R.R. Allmares, L. Wu, J.B. Swan, and G.W. Randall. 1990. Macroporosity and its relation to saturated hydraulic conductivity under different tillage practices. Soil Sci. Soc. Am. J. 54:1096–1101.

Logsdon, S.D., T.C. Kaspar, and C.A. Cambardella. 1999. Depth-incremental soil properties under no-till or chisel management. Soil Sci. Soc. Am. J. 63:197–200.

Luxmoore, R.J. 1981. Micro-, meso-, and macroporosity of soil. Soil Sci. Soc. Am. J. 45:671–672.

Luxmoore, R.J., P.M. Jardine, G.V. Wilson, J.R. Jones, and L.W. Zelazny. 1990. Physical and chemical controls of preferred path flow through a forested hillslope. Geoderma 46:139–154.

Meyer, L.D., S.M. Dabney, C.E. Murphree, and W.C. Harmon. 1999. Crop production systems to control erosion and reduce ruoff from upland silty soils. Trans ASAE 42:1645–1652.

Omoti, U., and A. Wild. 1979. Use of fluorescent dyes to mark the pathways of solute movement through soils under leaching conditions: 2. Field experiments. Soil Sci. 128:98–104.

Parker, J.C., and M.Th. van Genuchten. 1984. Determining transport parameters from laboratory and field tracer experiments. VA Agric. Exp. Stn. Bull. 84-3. Blacksburg, VA.

Perillo, C.A., S.C. Gupta, E.A. Nater, and J.F. Moncrief. 1998. Flow velocity effects on the retardation of FD&C Blue no.1 food dye in soil. Soil Sci. Soc. Am. J. 62:39–45.

Pikul, J.L., Jr., J.F. Zuzel, and D.E. Wilkins. 1988. Measurement of tillage induced soil macroporosity. Paper No. 88-1641. Am. Soc. Agric. Eng., St. Joseph, MI.

Rhoton, F.E., D.L. Lindbo, and M.J.M. Römkens. 1998. Iron oxides erodibility interactions for soils of the Memphis catena. Soil Sci. Soc. Am. J. 62:1693–1703.

Sauer, T.J., B.E. Clothier, and T.C. Daniel. 1990. Surface measurements of the hydraulic properties of a tilled and untilled soil. Soil Tillage Res. 15:359–369.

SAS. 1996. SAS/STAT Software: changes and enhancements through release 6.11. SAS Inst., Cary, NC.

Seyfried, M.S., and P.S.C. Rao. 1987. Solute transport in undisturbed columns of an aggregated tropical soil: Preferential flow effects. Soil Sci. Soc. Am. J. 51:1434–1444.

Shaw, J.N., L.T. West, C.C. Truman, and D.E. Radcliffe. 1997. Hydraulic properties of soils with water restrictive horizons in the Georgia coastal plain. Soil Sci. 162:875–885.

Singh, P., R.S. Kanwar, and M.L. Thompson. 1991. Measurement and characterization of macropores by using AUTOCAD and automatic image analysis. J. Environ. Qual. 20:289–294.

Thomas, G.W., and R.E. Phillips. 1979. Consequences of water movement in macropores. J. Environ. Qual. 8:149–152.

Triplett, G.B., S.M. Dabney, and J.H. Siefker. 1996. Tillage systems for cotton on silty upland soils. Agron. J. 88:507–512.

Trojan, M.D., and D.R. Linden. 1994. Tillage residue and rainfall effects on movement of an organic tracer in earthworm affected soils. Soil Sci. Soc. Am. J. 58:1489–1494.

Unger, P.W. 1996. Soil bulk density, penetration resistance, and hydraulic conductivity under controlled traffic conditions. Soil and Tillage Res. 37:67–75.

van Ommen, H.C., R. Dijksma, J.M.H. Hendrickx, L.W. Dekker, J. Hulshof, and M. van den Heuvel. 1989. Experimental assesment of preferential flow paths in a field soil. J. Hydrol. 105:253–262.

van Stiphout, P.J., H.A.J. van Lanen, O.H. Boersma, and J. Bouma. 1987. The effect of bypass flow and internal catchment of rain on the water regime in a clay loam grassland soil. J. Hydrol. 95:1–11.

Watson, K.W., and R.J. Luxmoore. 1986. Estimating macroporosity in a forest watershed by use of a tension infiltrometer. Soil Sci. Soc. Am. J. 50:578–582.

Wu, L., J.B. Swan, R.R. Allmaras, and S.D. Logsdon. 1995. Tillage and traffic influences on water and solute transport in corn-soybean systems. Soil Sci. Soc. Am. J. 59:185–191.

Zachmann, J.E., D.R. Linden, and C.E. Clapp. 1987. Macroporous infiltration and redistribution as affected by earthworms, tillage and residue. Soil Sci. Soc. Am. J. 51:1580–1586.